A Method for Quantifying Battery's Fast Charging Ability and Application to Different Lithium-Ion Chemistries

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***Abstract*—Wide adoption of lithium-ion batteries brings up the question of their fast charging ability which is still an issue in many applications. This is probably the most important for electric vehicles, but also for battery energy storage and even consumer electronics. Charging times can be reduced by using new battery materials, but also by using alternative charging strategies. This paper presents a novel method for quantifying battery's ability to accept charge in some arbitrary time interval. The proposed method can be used to quickly and effectively compare different battery technologies, different charging strategies or any possible charging condition that might be adjusted, while taking into account battery's charging ability throughout the entire state-of-charge range. This is achieved by introducing novel fast charging comparison metrics. The method is demonstrated by analyzing and comparing the fast charging ability of four lithium-ion battery cells of different chemistries. Input data are obtained experimentally, on a proprietary laboratory testbed.**

***Index Terms*—Lithium-ion batteries, fast charging, experimental research**

I. Introduction

The large penetration of lithium-ion batteries, together with the need for fast charging has resulted in a high research activity in this area. A thorough review of lithium-ion battery fast charging principles, materials, designs, strategies, as well as implications on degradation, thermal management and safety, is given in [1]. Comprehensive review of fast charging strategies and their applicability to battery electric vehicles (EVs) is presented in [2], where it is also stated that the reduction of EV charging times down to 15 minutes might be the solution to the range anxiety problem. A detailed, low-level analysis of different lithium-ion chemistries, their physicochemical properties and their influence on fast charging is presented in [3]. Influence of extreme temperatures on EV fast charging is addressed in [4]. A method for standardizing the comparison of the fast charging capability for different battery materials is proposed in [5]. This method is based on determining a figure of merit (FOM) which is calculated from diffusion coefficients and geometric sizes of battery materials. However, these electrochemical parameters might not always be available, which presents an obstacle for the wide adoption of the method. In contrast, the approach proposed in this paper is easily applicable to any battery, as it is based on an experimental recording of a battery charging characteristics. The only prerequisite is an appropriately sized battery charger.

Increasing charging currents with the aim to accelerate battery charging process comes with the cost of reduced safety (for some battery technologies) and reduced cycle life (faster battery degradation). These problems are tackled by two main approaches. One line of research focuses on new battery materials (chemistries) that could improve charging times, while the other focuses on different charging strategies.

The most widespread lithium-ion chemistries are: lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA) and lithium iron phosphate (LFP). Listed chemistries refer to the positive electrode construction material, while negative electrode is typically made out of graphite [6]. Main limitation on the charging rate of such batteries is the occurrence of lithium plating on the graphite negative electrode [3], [7]. Popular alternative to graphite is lithium-titanate which is also used as a negative electrode material. Such batteries are usually called lithium-titanium-oxide (LTO), regardless of the chemistry used for positive electrode (NMC, LFP or other). LTO batteries can be charged much faster than those with graphite negative electrode.

While many new materials show promising results [3], their time to market is hard to predict, which brings us to the other line of fast charging research: charging algorithms. Lithium-ion batteries are most commonly charged with CC-CV[1] method. Some of the alternative charging algorithms are [1]: CP-CV[2], MCC-CV[3], pulse charging, boost charging, variable current profile charging etc. Some of these methods have potential to either shorten charging times or improve battery's cycle life, or even both at the same time, as reported in the literature, see e.g. [1], [3]. In this paper conventional CC-CV charging is used for demonstration purposes, however proposed method can be used with any charging strategy.

Paper is organized as follows. Section II describes laboratory setup and tested battery cells, while experimental procedure is given in Section III. The proposed method is described in Section IV together with its application to compare fast charging of different lithium-ion chemistries. Conclusions are drawn in Section V.

[1]CC-CV=constant-current-constant-voltage
[2]CP-CV=constant-power-constant-voltage
[3]MCC-CV=multistage-constant-current-constant-voltage

II. Laboratory Setup

The experiments are conducted on a professional laboratory testbed consisting of: (i) bi-directional DC power supply Itech IT-M3413 [8], (ii) regenerative power system IT-M3622 [9] and (iii) proprietary NI LabVIEW cycling software.

Four different lithium-ion chemistries were tested and compared: LCO, NMC, LFP and LTO. All the tested cells are of the cylindrical 18650 type, with more detailed specifications provided in Table I.

TABLE I
SPECIFICATIONS OF THE TESTED BATTERY CELLS

Parameter	Cell 1	Cell 2	Cell 3	Cell 4
Chemistry	LCO	NMC	LFP	LTO
Type (dimensions)	18650	18650	18650	18650
Nominal capacity (Ah)	3.2	3.0	1.5	1.3
Nominal energy capacity (Wh)	12	10.8	4.8	3.12
Nominal voltage (V)	3.75	3.6	3.2	2.4
Charging voltage (V)	4.35	4.2	3.65	2.75
Discharge cut-off voltage (V)	2.75	2.5	2	1.6
Max. charge current	1C	1.33C	1C	10C
Max. discharge current	2C	6.67C	3.6C	10C
Cut-off current	0.05C	0.017C	0.02C	0.08C

III. Experimental Results

Each cell is subjected to the following test procedure on the IT-M3413 DC power supply:

1) Fully discharge the battery in CC-CV mode as follows. Cell is discharged with constant current of 1C[4] until the discharge cut-off voltage is reached (CC phase). After that voltage is kept at the discharge cut-off value, while the current gradually decreases to the current cut-off value (see Table I).
2) Fully charge the battery in CC-CV mode with 1C charging current. Procedure is the same as for discharging with the limiting voltage being the charging voltage value from Table I.

Since this paper is concerned with fast charging it makes sense to test each battery with its maximal allowable charging current, which for LTO cell is even 10C. However, in order to credibly compare different technologies, all the cells are charged with 1C which is maximal allowable charging current for the LCO and LFP cells, as given in their specification sheets. Nevertheless, in order to test the fast charging ability of LTO cell, one additional full charge is performed on IT-M3622 regenerative power system, by using the above test procedure with 1C in step 1) and 10C in step 2).

Thus, full charge half-cycles from 0% to 100% SOC[5] are obtained. The results are displayed in Fig. 1 and 2. Depicted SOC characteristics are obtained by the following expression:

$$soc(t) = soc(t-1) + \frac{100}{C}\int_{t-1}^{t} I^{\mathrm{ch}}(\tau)d\tau, \qquad (1)$$

where C is capacity corresponding to total Ampere-hours (Ah) charged during the full charge half-cycle and $I^{\mathrm{ch}}(t)$ is current logged during full charge.

Fig. 1 demonstrates that different lithium-ion chemistries have different charging characteristics for the same charging C-rate. The LCO cell has by far the longest charging time from 0% to 100% SOC. The LFP cell has the flattest voltage curve in intermediate (and relatively wide) SOC range, with voltage rising sharply when approaching the CV phase which typically lasts relatively short. On the other hand, the NMC cell has the steepest voltage curve during the CC phase. Flat voltage characteristics, typical for the LFP technology, are considered favorable because they imply that for constant current, power will also be (nearly) constant. The most important takeaway from Fig. 1 is that the CV phase lasts the longest for the LCO cell and the shortest for the LFP cell. Fig. 2 shows that at 10C, the LTO battery charges from 0% to 100% SOC in only little over 15 minutes. The CC phase lasts very short, as the

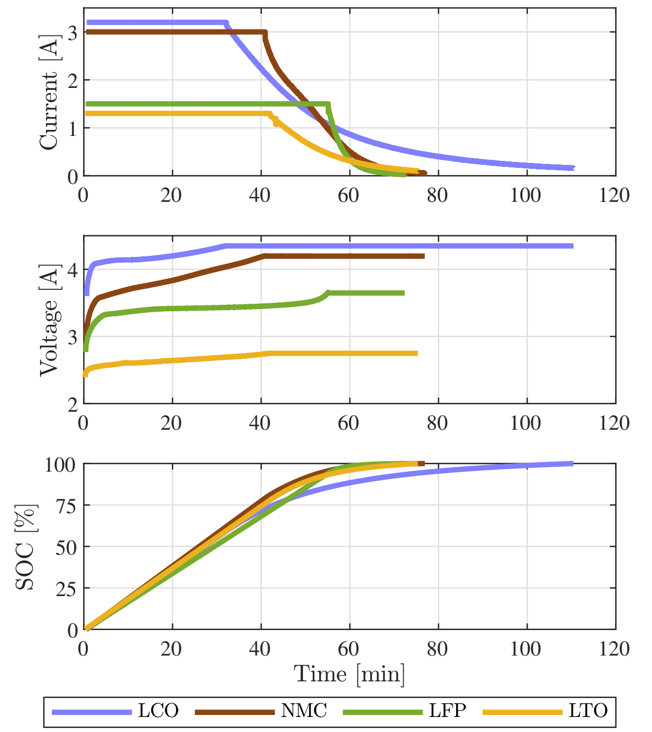

Fig. 1. Charging characteristics (1C) of the tested lithium-ion battery cells

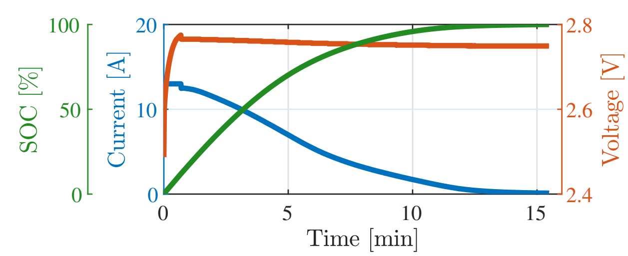

Fig. 2. Charging characteristics (10C) of the tested LTO battery cell

[4] C-rate specifies the speed at which the battery is being charged or discharged. The current of 1C corresponds to the cell's Ah-rating, e.g. for the LCO cell, 1C is 3.2 A.

[5] SOC=state-of-charge

voltage saturates quickly, however, the average current during the entire half-cycle is relatively high, which enables the cell to be fully charged in such a short period. Characteristics derived in the following section are based on SOC curves from Fig. 1 and 2.

IV. ΔSOC Method

The concept of SOE[6]-ΔSOE curves was introduced in [10], where it was used to model the battery hour-ahead charging ability in order to optimize scheduling of battery energy storage in the day-ahead market. The same concept is utilized in this paper with the aim of developing a method for reliable analysis and comparison of fast charging ability of either different lithium-ion chemistries or different charging strategies or any other charging condition. Compared to work in [10], the main difference in application of this concept is that SOC is used instead of SOE (by analogy) and that various ahead-intervals are considered.

The SOC-ΔSOC curves (term "ΔSOC curves" will be used for brevity) model how much charge a battery can absorb in some future time period, based on the current SOC. ΔSOC curves can be obtained by calculating the following expression:

$$\Delta soc(t) = soc(t+\Delta t) - soc(t), \forall (t+\Delta t) \leq T, \quad (2)$$

where $soc(t)$ is determined from battery's logged current during full charge via (1), $\Delta soc(t)$ is a change in SOC during time Δt which is some arbitrary ahead-interval of interest, while T is full charge duration. Now, ΔSOC curve is obtained by simply plotting $\Delta soc(t)$ as a function of $soc(t)$. This curve refers to a fixed value of Δt and a single full charge current characteristic $I^{\mathrm{ch}}(t)$ (typically nonlinear). Referring to (2), if $t+\Delta t > T$, the battery can be fully charged in less than Δt time and the ΔSOC curve coincides with the ideal 1 C-hour curve which is described next.

A. Ideal Curves

Fig. 3 displays two ideal ΔSOC curves. Such curves would be obtained for batteries that could reach full charge (100% SOC) by using the CC charging phase exclusively, which is not the case in reality[7].

The term "C-hour" appearing in the legend of Fig. 3 refers to the "C-rate-hour" as follows: 1 C-hour refers to the battery being charged for 1 hour with 1C, or for 30 minutes with 2C, or for 15 minutes with 4C etc. Likewise, 0.5 C-hour refers to the battery being charged for for 30 minutes with 1C, or for 15 minutes with 2C etc. Thus, an arbitrary number of ideal ΔSOC curves can be obtained for a battery, while a single curve can represent a different combination of C-rate (which is assumed to be constant) and Δt. The 1 C-hour is the highest possible ideal curve, i.e. this curve cannot be exceeded even for high C-rates and long ahead-intervals, purely because it is assumed that battery's SOC cannot exceed 100%.

[6]SOE=state-of-energy

[7]Equipment or battery manufacturers might oversize the battery to the point that the full charge (100% SOC) is pronounced when the charging voltage saturates and in this case ideal ΔSOC curve can be achieved.

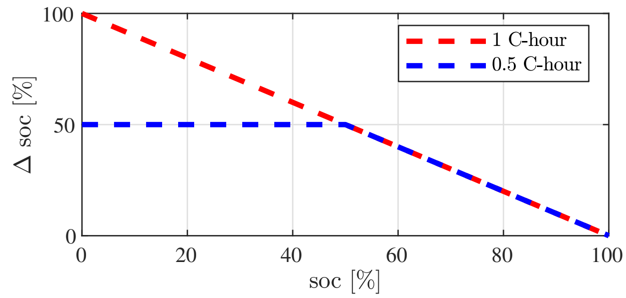

Fig. 3. Ideal SOC-ΔSOC curves

Let D^0 denote theoretical maximal ΔSOC amount by which a battery can be charged with the C-hour level of interest, starting from 0% SOC:

$$D^0 = R^{\mathrm{C}} \cdot \frac{\Delta t}{60} \cdot 100, \quad (3)$$

where R^{C} is the C-rate (considered constant), while Δt is the desired ahead-interval given in minutes. Then, the ideal ΔSOC curve consists of two lines, defined by the following three (SOC,ΔSOC) pairs: (0, D^0), (100 − D^0,D^0) and (100,0). In the case of 1 C-hour curve ($D^0 = 100$), first two points coincide at (0,100) and the ideal curve is a single line.

B. Real Curves

Fig. 4-8 present real (experimentally obtained) ΔSOC curves, together with the ideal curves. Each of these figures is based on the corresponding SOC characteristic from Fig. 1 and 2, respectively. Real curves are obtained by virtue of (1)-(2), while ideal curves are obtained as described above, with R^{C} entering the expression (3), calculated as:

$$R^{\mathrm{C}} = \frac{R^{\mathrm{A}}}{C}, \quad (4)$$

where R^{A} is charging current in Amperes, while C is actual Ah-capacity measured during the full charge half-cycle. Correction (4) is necessary for trustworthy comparison between real and ideal curves, since in practice, measured capacity deviates from the nominal capacity. Take 1C charging of a 3 Ah cell as an example. In an ideal case $C = C^{\mathrm{nom}} = 3$ Ah, $R^{\mathrm{A}} = 3$ A and $R^{\mathrm{C}} = 1$C. Now let $C = 2.73$ Ah be capacity actually measured. In this case $R^{\mathrm{C}} = \frac{3}{2.73} = 1.1$C and this is the value used for calculating D^0 and plotting ideal ΔSOC curve.

Hatched surfaces in Fig. 4-8 denote deviations of the real from ideal curves. The larger the surface, the larger the deviation and the worse (fast) charging ability for that particular Δt. For 1C charging (Fig. 4-7) it is clearly seen that the tested the LCO cell has the worst charging ability, while the tested LFP cell has the best charging ability. This is due to the fact that the LFP cell has the shortest CV phase during full charge. Furthermore, for longer ahead-intervals Δt, deviations of real from ideal curves are larger at low states-of-charge, while for

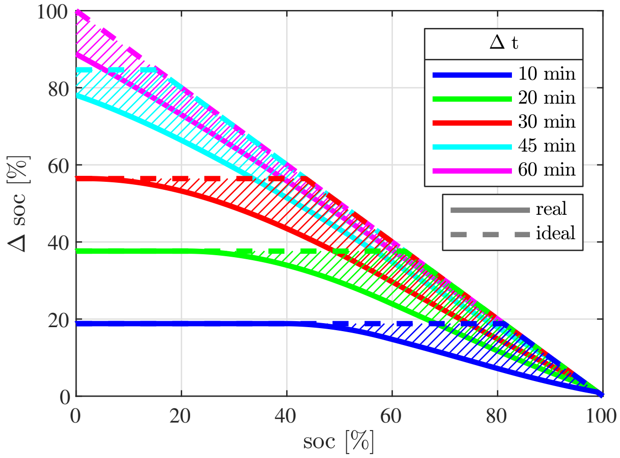

Fig. 4. LCO cell (1C charging)

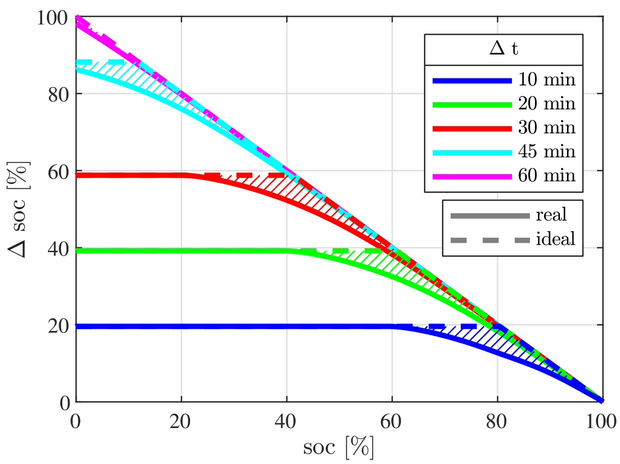

Fig. 5. NMC cell (1C charging)

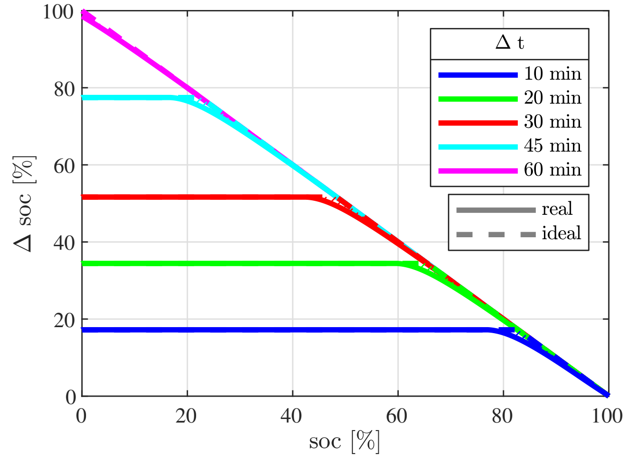

Fig. 6. LFP cell (1C charging)

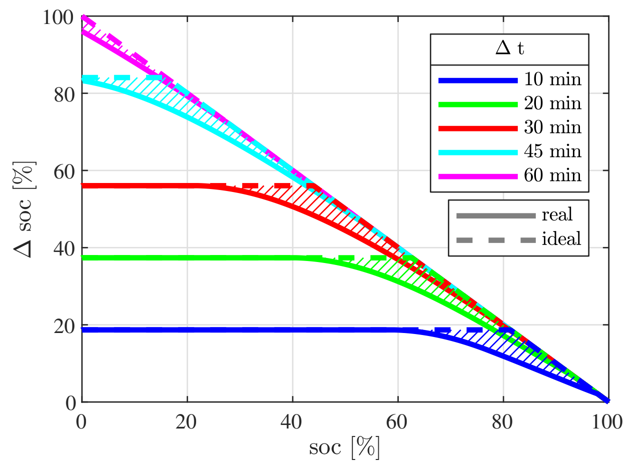

Fig. 7. LTO cell (1C charging)

shorter Δt intervals deviations are larger at intermediate and high states-of-charge. This is easily seen for the LCO, NMC and LTO curves and it is a consequence of cells' nonlinear charging characteristics where current gradually decreases as SOC approaches 100%.

For 10C charging (Fig. 8) deviations appear to be relatively high, but note that ahead-intervals Δt are extremely short. Taking red curve ($\Delta t = 5\text{min}$ as an example, LTO cell can charge from 20% to 80% in 5 minutes and its inability to charge from 20% to an ideal 100% is not a big downside since 5 minutes is relatively short period. This has to be kept in mind when interpreting deviations between real and ideal ΔSOC curves. Even a battery with poor fast charging ability will have its real curves converge towards ideal ones for ahead-intervals Δt high enough. The concept of ΔSOC curves can be used to compare different batteries or different charging algorithms for the same Δt as described in the next subsection.

C. Real Ideal Ratios

In order to compare different battery technologies (and/or different charging strategies), parameter "Real-Ideal-Ratio

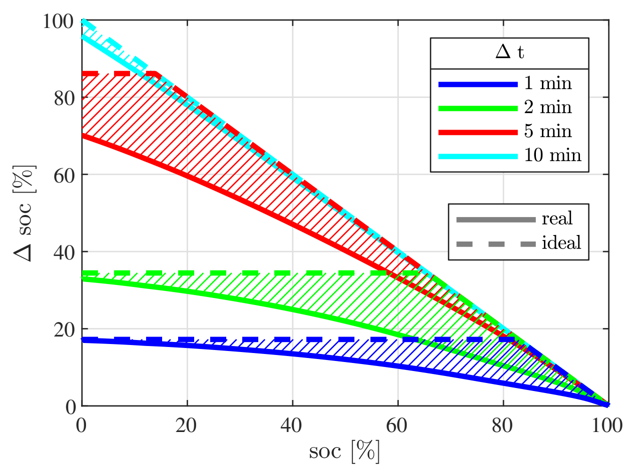

Fig. 8. LTO cell (10C charging)

(RIR)" is introduced and defined as follows:

$$RIR(\Delta t_i) = \frac{\int_0^{100} \Delta soc_{\Delta t_i}^{\text{real}}(soc)dsoc}{\int_0^{100} \Delta soc_{\Delta t_i}^{\text{ideal}}(soc)dsoc}, \quad (5)$$

where Δt_i is a particular ahead-interval (e.g. 10, 20, 30, 45 or 60 minutes), $\Delta soc^{\mathrm{real}}$ is a real and $\Delta soc^{\mathrm{ideal}}$ is an ideal ΔSOC curve. The expression (5) actually calculates ratios of surfaces under real and ideal curves, for the same Δt. The closer the value of RIR to 1, the smaller the deviation between a real and ideal curve.

By utilizing RIR parameter, results from Fig. 4-7 (1C charging of different cells) can be summarized and compared. This is presented in Fig. 9 from which the following conclusions can be drawn. The LFP cell has the best, while the LCO cell has the worst fast charging ability among the tested cells, which was obvious from Fig. 4 and 6. What was not obvious from Fig. 5 and 7 is that the NMC cell has slightly better fast charging ability than the LTO cells. Values of RIR increase as the ahead-intervals Δt prolong, the increase being steeper for cells with poorer fast charging ability. For the best performing LFP cell, the increase is very mild, as its $RIR(10)$ is already close to 1.

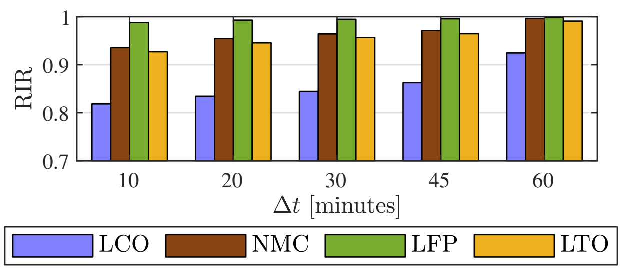

Fig. 9. Real-Ideal-Ratios (RIR)

D. Recapitulation

The proposed method is based on the concept of ΔSOC curves and it can be summarized as follows:

1) Obtain full charge characteristic $I^{\mathrm{ch}}(t)$ for the observed battery and/or charging strategy.
2) Obtain $soc(t)$ by cum. integration of $I^{\mathrm{ch}}(t)$, see (1).
3) Choose charging ahead-intervals of interest Δt_i.
4) For each Δt_i:
    a) Calculate $\Delta soc(t)$ as a function of $soc(t)$, see (2).
    b) Form vectors $SOC(j) = [soc(t)\ 100]$ and $\Delta SOC(j) = [\Delta soc(t)\ 0]$ which define real ΔSOC curve.
    c) Form ideal ΔSOC curve by calculating D^0 via (3)-(4) and connecting the three (SOC,ΔSOC) points: (0, D^0), (100 D^0,D^0) and (100,0).
    d) Calculate Real-Ideal-Ratio (RIR) via (5).
5) Repeat steps 1-4 for another battery or charging strategy.
6) Display and compare obtained real and ideal curves, as well as RIR values for all Δt_i and for all observed batteries (or charging strategies).

Note that determining ideal ΔSOC curves in step 4c) might not be straightforward in case of charging algorithms that use varying charging currents. In such cases the highest measured current can be taken as R^{A}, or alternatively the ideal 1 C-hour curve (see Fig. 3) can always be used as a reference.

The proposed method can analogously be applied for comparison of ΔSOE curves. In this case charging power $P^{\mathrm{ch}}(t)$ is used instead of current $I^{\mathrm{ch}}(t)$, while $soe(t)$ is used instead of $soc(t)$.

V. Conclusion

The paper presents a novel method for comparing battery's fast charging ability throughout the whole SOC range. The method can be used to analyze and compare charging performance of: different battery chemistries (lithium-ion or other), various charging concepts and algorithms (e.g. CC-CV, pulse charging, MCC-CV charging), charging under different environmental conditions (e.g. various temperatures) etc.

Upsides of the proposed method are simplicity and speed. The single full charging characteristic (0%-100% SOC) per tested battery/algorithm/condition has to be obtained as an input for the method. The downside of the proposed method is that it does not take battery degradation into account.

The method is demonstrated by using it to compare charging performance of four popular lithium-ion chemistries: LCO, NMC, LFP and LTO.

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References

[1] A. Tomaszewska, Z. Chu, X. Feng, S. O'Kane, X. Liu, J. Chen, C. Ji, E. Endler, R. Li, L. Liu, Y. Li, S. Zheng, S. Vetterlein, M. Gao, J. Du, M. Parkes, M. Ouyang, M. Marinescu, G. Offer and B. Wu, "Lithium-ion battery fast charging: A review," *eTransportation*, vol. 1, pp. 100011, 2019.

[2] N. Wassiliadis, J. Schneider, A. Frank, L. Wildfeuer, X. Lin, A. Jossen and M. Lienkamp, "Review of fast charging strategies for lithium-ion battery systems and their applicability for battery electric vehicles," *Journal of Energy Storage*, vol. 44, pp. 103306, 2021.

[3] M. Weiss, R. Ruess, J. Kasnatscheew, Y. Levartovsky, N. R. Levy, P. Minnmann, L. Stolz, T. Waldmann, M. Wohlfahrt-Mehrens, D. Aurbach, M. Winter, Y. Ein-Eli and J. Janek, "Fast Charging of Lithium-Ion Batteries: A Review of Materials Aspects," *Advanced Energy Materials*, vol. 11 (13), 2021.

[4] G. Trentadue, A. Rocha Pinto Lucas, M. Otura Garcia, K. Pliakostathis, M. Zanni and H. Scholz, "Evaluation of fast charging efficiency under extreme temperatures," *Energies*, vol. 11 (8), pp. 1937, 2018.

[5] H. Xia, W. Zhang, S. Cao, and X. Chen, "A Figure of Merit for Fast-Charging Li-ion Battery Materials," *ACS Nano*, vol. 16 (6), pp. 8525-8530, 2022.

[6] John T. Warner, "Lithium-Ion Battery Chemistries: A Primer," Elsevier Inc., 2019.

[7] M. T. F. Rodrigues, S. Son, A. M. Colclasure, I. A. Shkrob, S. E. Trask, I. D. Bloom, and D. P. Abraham, "How Fast Can a Li-Ion Battery Be Charged? Determination of Limiting Fast Charging Conditions," *ACS Applied Energy Materials* 2021 4 (2), pp. 1063-1068

[8] 'IT-M3400 Series User Manual', https://itechate.com/uploadfiles/%E7%94%A8%E6%88%B7%E6%89%8B%E5%86%8C/user%20manual/it-m3400/IT-M3400%20User%20Manual-EN.pdf, accessed 29 Nov 2022

[9] 'IT-M3600 Series User Manual', https://itechate.com/uploadfiles/%E7%94%A8%E6%88%B7%E6%89%8B%E5%86%8C/user%20manual/it-m3600/IT-M3600%20User%20Manual-EN.pdf, accessed 29 Nov 2022

[10] H. Pandžić and V. Bobanac, "An Accurate Charging Model of Battery Energy Storage," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 1416–1426, 2019.